

November 18, 2014

HFAG-charm averages

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The extraction of charm mixing and CP violation parameters requires the combination of many measurements. The latest averages are reviewed and the contribution of individual measurements is discussed. While it is established that the CP -even eigenstate is the shorter lived, the oscillation frequency of charm mesons is still not known to high accuracy. All CP asymmetries are found to be compatible with zero within less than 3σ .

PRESENTED AT

The
8th International Workshop on the CKM Unitarity Triangle
(CKM 2014)
Vienna, Austria, September 8-12, 2014

¹The author is supported by STFC, UK, under grant ST/J004332/1.

1 Introduction

The charm sub-group of the Heavy Flavour Averaging Group [1] provides averages and overviews of measurements in a diverse range of areas. These include mixing and CP violation, which are reviewed in more detail here, but also properties of excited charm states, leptonic and semi-leptonic charm decays, hadronic branching fractions, as well as baryonic, rare, and forbidden decays. The following section covers the extraction of mixing and indirect CP violation parameters, followed by a short summary of time-integrated asymmetries.

2 Mixing and indirect CP violation

The mass eigenstates of neutral charm mesons are denoted as $|D_1\rangle \equiv p|D^0\rangle + q|\bar{D}^0\rangle$ and $|D_2\rangle \equiv p|D^0\rangle - q|\bar{D}^0\rangle$, with complex coefficients satisfying $|p|^2 + |q|^2 = 1$. The parameter ϕ is the weak phase difference $\arg(q/p)$. The mixing parameters are defined as $x \equiv (m_2 - m_1)/\Gamma$ and $y \equiv (\Gamma_2 - \Gamma_1)/(2\Gamma)$, where $\Gamma = (\Gamma_1 + \Gamma_2)/2$. The convention used by HFAG is $(CP)|D^0\rangle = |\bar{D}^0\rangle$ and $(CP)|\bar{D}^0\rangle = |D^0\rangle$. Thus, in the absence of CP violation, $|D_1\rangle$ is CP -odd and $|D_2\rangle$ is CP -even.

The extraction of the parameters describing mixing and indirect CP violation in the charm system requires the combination of many measurements. In total, 45 measurements are used to extract ten parameters whose results are summarised in Table 1. Due to the interplay of direct and indirect CP violation, some parameters describing direct CP violation in Cabibbo-suppressed decays have to be included [2, 3]. The average [1] yields no indication of CP violation. Charm mixing on the other hand is well established with y being confirmed to be positive, indicating that the CP -even state is the shorter lived. The precision on x is significantly worse and this parameter is currently not significantly non-zero (2.4σ). This can be improved particularly through measurements of $D^0 \rightarrow K_s^0 \pi^- \pi^+$ decays as is discussed in more detail below.

There is a remarkable difference in sensitivity between the scenario allowing for all types of CP violation and that using the so-called superweak approximation. The latter introduces the relation $\tan \phi = (1 - |q/p|^2)/(1 + |q/p|^2) \times (x/y)$, which reduces the number of parameters by one [1, 2, 4]. In addition, the parameters can also be expressed as x_{12} , y_{12} and ϕ_{12} , which are more closely connected the parameters of the mass and width matrices describing charm mixing [1, 2].

A number of measurements have been added since the last CKM workshop. These are mostly measurements of two-body hadronic final states apart from an updated measurement of $D^0 \rightarrow K_s^0 \pi^- \pi^+$ decays by the Belle collaboration [5]. New measurements using $D^0 \rightarrow K^+ \pi^-$ decays have been provided by the CLEO [6], LHCb [7, 8], CDF [9], and Belle [10] collaborations. The BaBar and Belle collaborations updated their measurements of the observables y_{CP} and A_Γ using their full data samples [11, 12].

Table 1: Results of the global fit for different assumptions concerning CP violation. Reproduced from Ref. [1]

Parameter	No CPV	No direct CPV in DCS decays	CPV-allowed	CPV-allowed 95% CL Interval
x (%)	$0.49^{+0.14}_{-0.15}$	$0.43^{+0.14}_{-0.15}$	$0.41^{+0.14}_{-0.15}$	[0.11, 0.68]
y (%)	0.62 ± 0.08	0.60 ± 0.07	$0.63^{+0.07}_{-0.08}$	[0.47, 0.76]
$\delta_{K\pi}$ ($^\circ$)	$7.8^{+9.6}_{-11.1}$	$4.6^{+10.3}_{-12.0}$	$7.3^{+9.8}_{-11.5}$	[-18.5, 25.8]
R_D (%)	0.350 ± 0.004	0.349 ± 0.004	0.349 ± 0.004	[0.342, 0.356]
A_D (%)	—	—	$-0.71^{+0.92}_{-0.95}$	[-2.6, 1.1]
$ q/p $	—	$1.007^{+0.015}_{-0.014}$	$0.93^{+0.09}_{-0.08}$	[0.79, 1.12]
ϕ ($^\circ$)	—	$-0.30^{+0.58}_{-0.60}$	$-8.7^{+8.7}_{-9.1}$	[-26.9, 8.6]
$\delta_{K\pi\pi}$ ($^\circ$)	$18.7^{+23.2}_{-23.7}$	$20.8^{+23.9}_{-24.3}$	$23.3^{+23.9}_{-24.4}$	[-24.8, 70.2]
A_π (%)	—	0.11 ± 0.14	0.14 ± 0.15	[-0.15, 0.42]
A_K (%)	—	-0.13 ± 0.13	$-0.11^{+0.14}_{-0.13}$	[-0.37, 0.15]
x_{12} (%)	—	$0.43^{+0.14}_{-0.15}$		[0.13, 0.69]
y_{12} (%)	—	0.60 ± 0.07		[0.45, 0.75]
ϕ_{12} ($^\circ$)	—	$0.9^{+1.9}_{-1.7}$		[-3.0, 6.1]

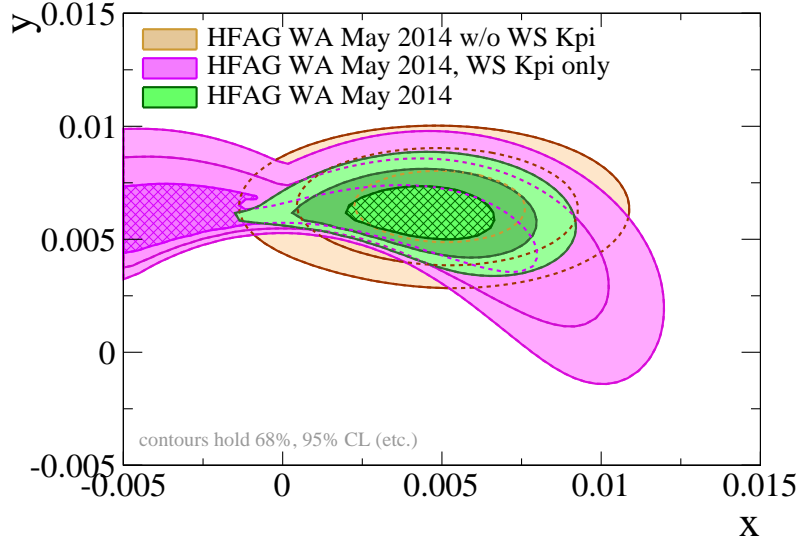


Figure 1: Contributions of the combination of different measurements to the extraction of the parameters x and y .

The LHCb collaboration has published a measurement of A_Γ based on a part of their dataset [13]. Finally, LHCb has released measurements of the difference in direct CP asymmetry in two-body singly Cabibbo-suppressed decays [14–16]. In the following the impact of these measurements is reviewed.

Measurements using $D^0 \rightarrow K_s^0 \pi^- \pi^+$ provide direct access to x and y and thus yield an elliptical contour in a plot showing the allowed ranges for y vs x (see Fig. 1). Adding measurements of y_{CP} constrain y further in the absence of CP violation. This is shown as the brown contour in Fig. 1. Measurements using $D^0 \rightarrow K^+ \pi^-$ decays yield constraints on y' and $x^2 + y^2$, where $y' \approx y$ since the strong phase $\delta_{K\pi}$ is known to be close to zero. This leads to a contour that is symmetrical around $x \approx 0$ and that roughly describes an ellipse around zero for a range in y (see pink contour in Fig. 1). The green contour in Fig. 1 shows the full combination of all measurements, to which measurements that were not explicitly mentioned here do not contribute significantly. This shows that additional measurements of $D^0 \rightarrow K_s^0 \pi^- \pi^+$ decays will be essential to constrain x and to determine its sign with higher significance.

Similarly to the parameters x and y , the CP violation parameters $|q/p|$ and ϕ are measured directly using the decay $D^0 \rightarrow K_s^0 \pi^- \pi^+$. The resulting elliptical contour is further constrained in one direction by the addition of measurements of the observable A_Γ , which determines indirect CP violation. This is shown in the brown contour in Fig. 2. Measurements using flavour-tagged $D^0 \rightarrow K^+ \pi^-$ decays yield the pink contour in Fig. 2, which shows particularly good sensitivity to $|q/p|$ for small absolute values of ϕ . The green contour in Fig. 2 shows the full combination of all measurements,

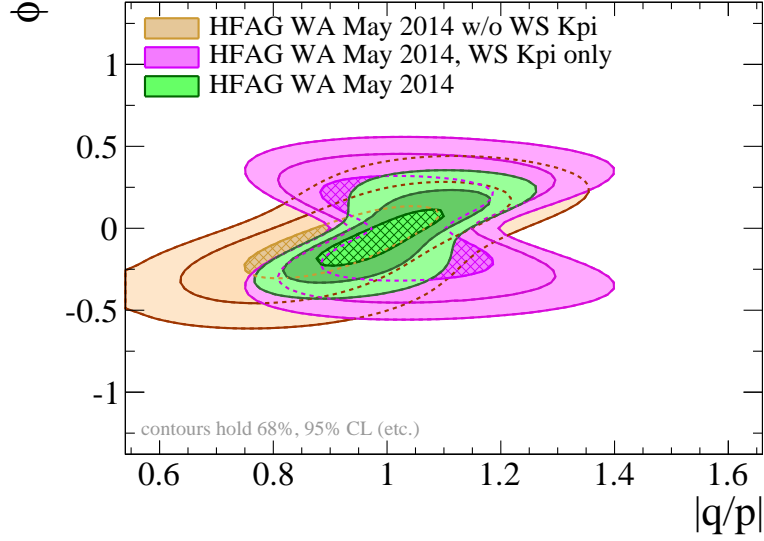


Figure 2: Contributions of the combination of different measurements to the extraction of the parameters $|q/p|$ and ϕ .

to which measurements that were not explicitly mentioned here do not contribute significantly.

A question arising from these averages is whether there is a tension between the measurements of y_{CP} and those constraining y directly. For roughly similar magnitudes of x and y it is expected that the relation $y_{CP} \lesssim y$ holds unless $|q/p|$ deviates strongly from unity. As is shown in Fig. 3, the world average of y obtained from all inputs but y_{CP} does not fully coincide with the world average of y_{CP} . However, this discrepancy is not very significant ($< 2\sigma$). Thus, while a stronger tension may have existed with older measurements, there is no inconsistency at present.

A dedicated average comparing indirect CP asymmetry measurements with the difference of direct CP asymmetries in D^0 decays to K^-K^+ and $\pi^-\pi^+$ mesons yields $a_{CP}^{ind} = (0.013 \pm 0.052)\%$ and $\Delta a_{CP}^{dir} = (-0.253 \pm 0.104)\%$. With a confidence level for the no CP violation hypothesis of 5.1%, this average also shows no evidence for CP violation.

3 Time-integrated asymmetries

A number of time-integrated asymmetry measurements have been published since the last CKM workshop. These measurements have been averaged with existing measurements where available. None of these averages shows a significant deviation from zero.

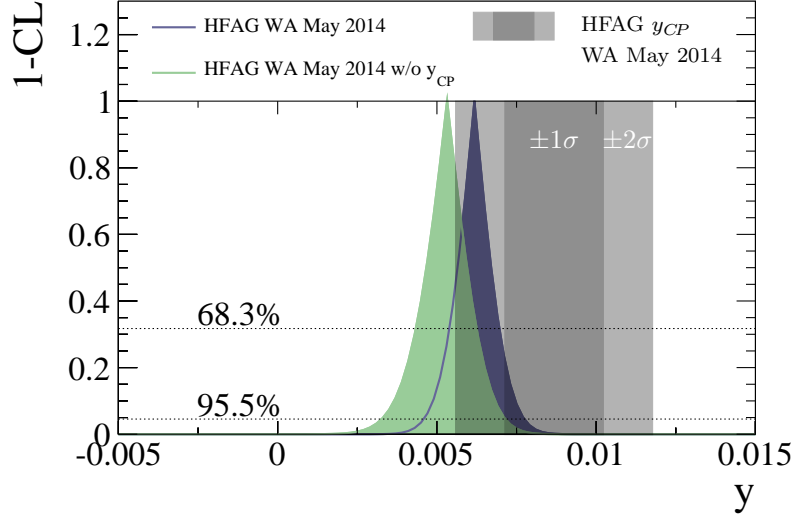


Figure 3: Comparison of the world average for y with and without using measurements of y_{CP} (shown as likelihood contours) with the world average of y_{CP} (shown as bars).

The range of measurements includes a comprehensive study of hadronic final states of D^0 , D^+ , and D_s^+ decays by the CLEO collaboration [17, 18]. The LHCb collaboration has released measurements of D^+ and D_s^+ decays into hadronic final states involving K_s^0 mesons [19]. The Belle collaboration has published measurements of D^0 decays into two neutral mesons [20].

4 Conclusion

In summary, there has been enormous progress in improving the precision of charm mixing and CP violation parameters over the past two years. However, of the two mixing parameters x remains rather weakly constrained. Initial evidence for CP violation in the charm sector is currently not confirmed. Significant progress is still to be expected from the completion of all of LHCb's measurements based on data taken during the first run of the LHC. These measurements are likely to dominate the picture at the next CKM workshop. Beyond that, the LHCb run-2 and upgrade programme as well as Belle II will allow the exploration of CP asymmetries to a level of precision around 10^{-4} , thus probing down to the Standard Model level. In addition, important contributions are expected from BES-III as the only running experiment capable of exploiting quantum-correlated charm-anticharm systems.

ACKNOWLEDGEMENTS

The author acknowledges support from Moritz Karbach in preparation of some of the material presented here.

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